

# CIRCUIT AND METHOD FOR CONTROLLED INDEPENDENT RECYCLE OF DISCHARGE CURRENT OF MULTIPLE INDUCTIVE LOADS

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

This invention relates to a circuit and method for controllably and independently recycling the discharge current of a plurality of inductive loads connected between first and second power supply terminals.

### 2. Discussion of the Related Art

Throughout the description to follow, the invention will be discussed, by way of non-limitative example, as applied to electronic systems specifically intended for automotive use which comprise devices having inductive loads connected in the manner mentioned above.

As is known, a number of electronic and electromagnetic devices, arranged to perform a variety of functions in motor cars, include one or more inductive loads. Such devices also distinguish themselves by the current that their respective loads are to withstand. Some inductive loads are of relatively small size and can only withstand moderately large currents during their operation. Devices of this kind may include relays of several different types, for example. On the other hand, there are inductive loads of larger size, such as those contained in fuel injection control devices, which can store larger amounts of energy.

In the systems referred to hereinafter, each inductive load usually has one terminal which is kept at a fixed voltage and another terminal connected to a preferably integrated control circuit driving the flow of current through the load.

Two configurations are known in the art wherein the fixed voltage terminal of the load is connected either to the power supply line or to ground. In the former case, the load is driven from its lowest voltage terminal, in a so-called low-side driver configuration, whereas in the latter case, the configuration is that known as high-side driver.

The control circuit comprises an active element, such as a driving transistor, which in most cases is a power transistor and performs switching functions to alternately force and interrupt the flow of current through the inductor. The active element is controlled by a drive signal generated within the circuit itself.

It is well recognized that the driving of markedly reactive loads, as inductive loads happen to be, generally causes some problems during the transients. In fact, upon cutting off the flow of current through an inductor, a voltage increase, i.e. an overvoltage, instantaneously appears across it which may be positive or negative depending upon the specific circuit design. This overvoltage is due to the energy previously stored in the inductor during the charging phase and generated by the flow of electric current forced through the inductor remaining constant even after the flow of current is cut off. Thus, an electromotive force is induced which tends to keep the current at the value attained during the "on" period, i.e. during the charging phase. Since the load has one terminal at a fixed potential, the increase in potential will occur at the other terminal, i.e. the terminal for connection to the control circuit.

For the device to operate as designed, the voltage peak should have limited width, for otherwise the peak could cause breakdowns in the junctions of the semiconductor elements present in the control circuit, or in other devices connected to this circuit. Where the circuit is integrated

monolithically, the overvoltage may fire parasitic transistors, and ultimately cause the device to breakdown.

As is known to skilled persons in this art, to reduce the overvoltage a means may be provided for dissipating the energy stored up in the inductor, i.e. a means enabling a discharge current from the inductor to be recycled. The energy built up in the inductive load is dissipated by causing current to flow through pre-arranged elements, usually power ones.

In conventional approaches, the recycling circuit also functions to regulate the voltage increase. While the current is being recycled, the voltage on the inductive load reaches a maximum value which is set by the recycling means itself. This voltage limiting effect is called "clamping" in the pertinent literature. The value of the clamped voltage at that maximum remains constant through a given time interval, to then decrease in absolute value, simultaneously with the current, down to a zero value which corresponds to a fully discharged inductive load.

The duration of the discharging phase, i.e. the so-called discharge time, is tied directly to the maximum voltage value reached on the inductor.

The discharge time is of particular consequence. It is frequently important that the discharge time be controlled accurately. For example, with devices for automotive use, it is on the basis of this time that logic control circuits operatively connected to the devices are correspondingly set. In addition, if the device is a fuel injector which is controlled to open and close by the presence or absence of a current flow through the load, it is important that the control current flowing through the load can be cut off within a short time, so that the closing time of the injector can be made short and a precise amount of fuel injected.

The discharging phase is regulated by suitably sizing the recycling circuit to correspondingly select the maximum voltage value.

It is convenient if this regulation can be performed substantially independent of changes in outside conditions, such as ambient or fabrication temperature, or process spread in the instance of integrated circuits.

In accordance with the prior art, a well-known class of circuit designs, to which this invention is related, have been provided to recycle the current through the same transistor which is to drive the inductive load and already arranged to accept the discharge current peak through it, this usually being a power element. A recycling regulating circuit is connected between the load terminal arranged to be connected to the control circuit, that is to the driving transistor, and a control terminal of the transistor. That circuit will control the value of the voltage present on the load and automatically turn on the transistor when this voltage reaches a predetermined maximum value. In the field of automotive devices, this voltage maximum value is commonly on the order of a few tens volts, a typical value for a fuel injector being 70 volts, for example.

Those circuit elements which define the maximum voltage value represent, within the recycling regulating circuit, what throughout the following description will be referred to as the "reference for the voltage".

A variety of conventional designs exist in this field.

A first solution provides one or more Zener diodes connected between the control terminal of the driving transistor and the inductive load. The Zeners constitute the reference for the voltage in this case, the maximum voltage being a combination of the Zener voltages.

Shown diagrammatically in FIG. 1 is one such circuit. In this example, the inductive load L is connected in a low-side driver configuration, it having one terminal connected to the supply line  $V_s$  and the other terminal to the drain terminal D of a MOS driving transistor, here an N-channel type 5 denoted by TM. The transistor TM has its source terminal connected to ground. Connected to the gate G, forming the control terminal of TM, is a driver circuit schematically illustrated by the block C. Connected in series between the gate G and the node D, are a number, n, of Zener diodes 10 schematically indicated at nZ in the Figure. The Zeners are configured to set the maximum voltage at the node D to a value  $V_{max} = nV_z + V_{GS}$ , where  $V_z$  is the Zener voltages and  $V_{GS}$  is the drop in potential across the gate and the source of the transistor TM. As, upon the transistor TM being 15 turned off, the voltage at the node D attains the value  $V_{max}$ , the transistor TM will go into conduction, thereby allowing the current to be recycled and discharging the inductor L.

A drawback of this circuit is that the maximum voltage value on the inductor, as determined by the combination of 20 a discrete number of Zener voltages, may not equal exactly the desired one. In the instance of an integrated circuit, it should not be overlooked, moreover, that if the maximum voltage value is fairly high, then the number of the Zeners and the area occupied by the recycling regulating circuit is greater than negligible. The voltage value of the Zener 25 diodes also is liable, as is well recognized, to be indeterminate due to significant process spread.

Another prior circuit solution, which represents a substantial improvement on the first, is shown in FIG. 2. This 30 provides one or more additional transistors in the recycling circuit.

In FIG. 2, corresponding elements are denoted by the same references as in FIG. 1. The recycling regulating 35 circuit further comprises at least one transistor Q of the bipolar type, connected between the gate G and the node D. The Zener diodes nZ are here connected between the base and the collector of the transistor Q. The maximum voltage at the node D is set to the value  $V_{max} = nV_z + V_{BE} + V_{GS}$ , 40 where  $V_{BE}$  is the drop in potential between the base and the emitter of the transistor Q. Thus, the maximum clamping voltage will be the resultant of a combination of a larger number of voltage drops than in the circuit previously described. The transistor Q functions to absorb possible 45 excess currents and prevent the Zener from being burned. The resistor R, depicted in series with the Zener diodes in FIG. 2, is also effective to limit the current.

Neither of the circuits just described has good stability. In fact, since the voltages across the Zeners have different 50 dependence on temperature, temperature compensation can only be achieved for certain definite maximum voltage values.

For the purpose, the prior art provides still more sophisticated and precise solutions. For example, one conventional 55 circuit design provides for the use of a recycling regulating circuit which includes a voltage divider and a comparator. A circuit of that kind is disclosed in European Patent Application EP-0622717.

Such a circuit is illustrated in schematic form by FIG. 3. 60 The voltage divider R1-R2 is connected between the inductive load L and a ground terminal. The comparator COMP has two inputs respectively connected to the output of the voltage divider and to a generator of a reference voltage  $V_{ref}$ , and has an output coupled to the gate terminal G of the 65 driving transistor TM. In the example of FIG. 3, the circuit further comprises a current mirror M having an input leg

connected to the output of the comparator COMP and an output leg connected to the gate terminal G. The mirror M is also supplied to the node D.

Basically therein, the reference voltage is compared with a divided value of the voltage to be regulated which is present on the node D. Current recycling takes place upon the voltage value  $V_{max} = V_{ref}(R1+R2)/R2$  being reached on the node D. The reference for the voltage comprises that voltage reference circuit and the divider. Since the variation in the maximum voltage depends on a voltage reference which can be easily selected to be a stable one temperature-wise, that recycling regulating circuit is quite stable temperature-wise.

The systems to be specifically discussed in connection with the invention include, as previously mentioned, a plurality of inductors. For example, in the instance of plural automotive devices wherein the different inductive loads require driving on an individual basis and must be operated each independently of the others, the recycling of the 10 discharge current from each load should take place at different times from the other loads, and the discharging time required may not be the same for all the loads.

It will be appreciated that the principles of this invention can also be applied to devices of a different kind, e.g. those used in industrial systems employing multiple stepper 15 motors.

To provide independent recycling for different inductive loads, it has been common practice to recycle current through a plurality of recycling regulating circuits, each 20 connected to a respective one of the loads. The overvoltage clamping is done with a separate reference for each load.

The reference for the voltage may be provided in any desired way. In general, circuits incorporating Zeners like those shown in FIGS. 1 and 2 are used. However, the combination of a number of such circuits, of the types 25 previously described, has some disadvantages. The overall number of Zeners employed actually tends to be fairly large. To ensure restoration of a plurality of driving transistors to the on state in an independent manner, it is necessary that a separate series of Zeners be connected to each transistor, so as to directly limit the voltage to the respective node D for connection to the load and leave the operation of the other transistors unaffected. However, the number of the Zeners 30 may be of about ten in each series, at the aforementioned maximum voltage values, which means that a very large area of the integrated circuit will be occupied.

Even where recycling circuits of the type shown in FIG. 3 are used, in order to ensure independence of recycling for the various loads, because it would be disadvantageous to 35 uncouple the renewed turning on of the driving transistors, and hence the recycling, in any other ways, a corresponding number of dividers and comparators must be provided, which again poses problems of area occupation.

A technical problem that underlies this invention is to provide a circuit for independently recycling a plurality of inductive loads connected between two power supply terminals, which circuit can be integrated monolithically within a small integration area.

An object of this invention is to provide a recycling circuit which is stable to variations in ambient conditions, such as temperature, and to varying parameters during its manufacture.

#### SUMMARY OF THE INVENTION

A circuit according to an embodiment of the invention includes, for each of a plurality of independent loads: an

active element connected in series with the respective inductive load and having a control terminal to which a driver circuit is connected; and a regulator means for controlling the recycle of the discharge current from the respective load, connected to the control terminal of the active element and to a node for connection between the active element and the respective inductive load.

An idea on which the invention stands is that of providing a recycling circuit for plural inductive loads, which comprises, for each inductive load, at least one circuit element which allows the turning on of the driving element of one load to be uncoupled from that of the others. In this way, independent recycling of each load can be ensured while using a single common reference.

A monolithically integrated circuit for controllably and independently recycling the discharge current of a plurality of inductive loads connected between first and second power supply terminals comprises, for each of the loads, an active element and a regulator means for controlling the recycling of the discharge current of a respective one of the loads. The active element is connected in series with the inductive load between the two supply terminals, and has a control terminal to which a driver circuit is connected and which is coupled through an impedance to the supply terminal of lower potential. The regulator means is connected to the control terminal of the active element and to a node for connection between the active element and the respective inductive load.

According to an embodiment of the invention, the recycling circuit includes a single voltage reference  $V_{ref}$ .

In accordance with an embodiment of this invention, the regulator means for recycling control includes a blocking and triggering element and a circuit means for generating a turn-on signal to be applied to the control terminal of the active element. The blocking and triggering element is connected to the voltage reference, which is common for the whole circuit, and is coupled to the node for connection to the load. This circuit means is connected to the control terminal and operatively connected to the blocking and triggering element. Preferably, it may also be connected to the node for connection. The blocking and triggering element will act on the circuit means to generate the turn-on signal and only start the recycling of the current through the active element when the potential at the node for connection to the load is significantly higher in absolute value than the reference potential. Otherwise, the blocking and triggering element would block the flow of current through said circuit means.

The blocking and triggering element permits the control terminal of the active elements for the different inductive loads to be uncoupled by acting thereon as a sensor of the voltage value present on the node for connection and as a recycling activator.

Particularly, in an embodiment of the invention, the circuit means for generating the turn-on signal comprises a current mirror. Also, the blocking and triggering element may be a diode which will be forward biased when the potential at the terminal for connection to the respective load is significantly higher in absolute value than the reference potential.

Based on the above solvent idea, the technical problem is solved by an integrated circuit for recycling a plurality of inductive loads, of the type described hereinabove.

The features and advantages of a recycling circuit according to the invention will be apparent from the detailed description of an embodiment thereof, given by way of

example and not of limitation with reference to the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 shows in diagram form a prior art recycling circuit for a single inductive load, whose operation has been described in the foregoing;

FIG. 2 illustrates a prior art improvement on the circuit shown in FIG. 1;

FIG. 3 illustrates a prior art recycling circuit which is uniquely temperature stable and has been discussed in the foregoing;

FIG. 4 is a comprehensive diagram of a system which incorporates a circuit for independently recycling a plurality of inductive loads, in accordance with an embodiment of this invention;

FIG. 5 is a functional block diagram of a portion of the circuit in FIG. 4 related to a first inductive load; and

FIG. 6 illustrates an exemplary embodiment of a recycling circuit according to an embodiment of the invention, for application in a low-side driver configuration.

## DETAILED DESCRIPTION

FIG. 4 is a block diagram of a device which includes a circuit for controllably and independently recycling the discharge current of a plurality of inductive loads embodying this invention. The figure shows a number,  $N$ , of inductive loads  $L_1, L_2, \dots, L_N$  connected between first and second power supply terminals which are respectively kept at constant voltages  $V_a$  and  $V_b$ . The number  $N$  of inductive loads may be on the order of a few tens.

The lines  $V_a$  and  $V_b$  typically represent power supply and ground lines. Both the low-side configuration, with  $V_a$  corresponding to the supply voltage, and the high-side configuration, with the supply line being denoted by  $V_b$ , are encompassed by this invention.

Connected to the  $N$  inductive loads is a driver and recycling circuit according to an embodiment of the invention, as generally shown at 1. The circuit is preferably an integrated circuit and has a number,  $N$ , of terminals  $D_1, D_2, \dots, D_N$  for connection to the inductive loads.

Circuit 1 comprises, for each the inductive load, an active element  $T_n$ , where  $n=1, \dots, N$ , which is connected in series with the respective inductive load between the two supply terminals. Specifically, and as shown in FIG. 4, the active element  $T_n$  is connected to the respective node  $D_n$  and the supply terminal  $V_b$ . A regulator means, schematically represented by the block  $2n$ , for controlling the recycling of the discharge current of the inductive load  $L_n$ , is connected to the node  $D_n$  and the control terminal  $DR_n$  of the active element  $T_n$ . The regulator means  $2n$  is further connected to a reference circuit, to be also indicated as the potential reference hereinafter, which generates a reference voltage  $V_{ref}$  within the circuit 1.

In accordance with an embodiment of this invention, and as shown in FIG. 4, there may be a single potential reference which is common for the whole circuit. Such a reference may determine the maximum voltage value for triggering the recycling of the inductive loads.

The inductive load  $L_n$  driving takes place directly through the active element  $T_n$ , functioning as a switch to regulate the flow of current through the respective  $L_n$ . A driver circuit  $C_n$  is operatively connected to a control terminal

7  
 DRn of the active element Tn to alternatively drive it on and off. The driver circuits Cn operate independently to permit operation of the N inductive loads. In practice, each circuit Cn acts on its corresponding active element and the latter, once turned on, forces a current flow through the inductor Ln.

Upon the driver circuit Cn cutting off the flow of current through the inductive load Ln, and the current must then be flowed back as described, the regulator means 2n will allow the current to be recycled from the inductive load Ln through Tn. Specifically, the regulator means 2n functions as a sensor of the voltage value present on the specific node Dn for connection and determines the way that the corresponding active element Tn is to be turned back on, based upon a comparison with the value of the reference voltage Vref.

A more detailed scheme of operation for a portion of the recycling circuit relating to a single inductive load is shown in FIG. 5. The same references are used in this figure as in FIG. 4 to denote similar blocks and elements.

FIG. 5 shows the inductive load L1, by way of example, but the scheme applies equally well to each of the other loads.

As shown in FIG. 5, the regulator means 21 comprises, in accordance with this invention, a blocking and triggering element 31 which is connected to the potential reference Vref and coupled to the node D1 for connection between the active element T1 and the inductive load L1. A circuit means 41 connected to the control terminal DR1 is arranged to generate a turn-on signal for application to the control terminal DR1. The control terminal DR1 is operatively acted upon by the blocking and triggering element 31. Preferably, though not necessarily, this circuit means 41 is powered via the node D1 for connection.

In practice, the circuit of FIG. 5 operates as follows. The voltage at the node D1, which would be raised on account of the abrupt interruption in the current flow caused by the active element T1 being turned off, can attain a predetermined value VmaxD1 which is related to the reference value Vref. The element 31 will at that point be acting on the circuit means 41 to cause generation of the above turn-on signal. This signal generated by the circuit means 41 again enables the flow of current through the active element T1, with consequent discharging of the inductive load.

Specifically, the blocking and triggering element 31 performs a comparison of the potential present on the node for connection D1 with the constant value Vref. It is only activated when the potential at the node D1 is significantly higher in absolute value than the reference potential Vref. On the other hand, as long as the potential on the node D1 keeps within acceptable values, i.e. below VmaxD1, the element 31 will function as a blocking element to inhibit operation of the means 41.

The reference for the voltage according to an embodiment of this invention consists basically of the potential reference Vref; that is, the maximum voltage value for recycling triggering is substantially dependent on the value of Vref.

The blocking and triggering element 31 functions to uncouple the control terminal DR1 of the active element T1 from the potential reference Vref. Accordingly, all the control terminals DRn will be uncoupled from one another. This allows a single voltage reference to be provided within the driver circuit 1 of the N inductive loads, while ensuring independent triggering for the different active elements Tn, with the latter being each allowed to recycle whenever necessary.

This means that it can be assumed, for example, that at a time t0, one load, for example L1, will be in a turning on

phase, and the voltage at the node Di approximately equal to Vb but for the potential drop across the active element. Another active element Tk will be off, and no current will be flowing through Lk. The flow of current through a further inductive load Lj may be cut off at that time t0, so that an overvoltage will appear on a node Dj. According to the invention, a discharge current would be recycled through the load Lj only.

The potential reference Vref may be included into the circuit as shown in FIG. 4. This reference may be provided by any generator of a constant voltage. For example, the voltage Vref may be derived from the output of a voltage regulating circuit, or of a band-gap type of voltage multiplier. Also notice that the value of the voltage Vref may be either positive or negative, depending on specific applications.

The control terminal DR1 of the active element T1 may be further coupled to the lower supply voltage terminal Vb through an impedance Z1, as shown in FIG. 5. The latter may represent one or more resistive loads. However, where the transfer speed of the turn-on signal, that is the discharge time of the terminal DR1, is of no concern, Z1 may comprise one or more capacitive loads.

Advantageously according to an embodiment of the invention, the circuit for recycling the N loads makes for a smaller bulk or occupied area than in the conventional circuit designs previously discussed. This because it is unnecessary to provide a number N of references for the voltage, as already explained. However, the blocking and triggering elements 3n and circuit means 4n may be small in size, as explained hereinafter in connection with one embodiment.

The recycling circuit embodying this invention is advantageously stable, in that the maximum voltage value for recycling triggering is mainly dependent on the reference Vref. The potential reference may be selected to be uniquely stable to changes in ambient conditions, in particular to be unaffected by temperature. Thus, the operational conditions for the circuit triggering are made independent of random parameters.

A wiring diagram is specifically depicted in FIG. 6 for a preferred embodiment. In FIG. 6, the blocks shown in the preceding figures have been denoted by the same references for clarity.

The embodiment of FIG. 6 shows the N inductive loads Ln connected in a low-side driver configuration, that is with one terminal connected to a supply line Vs and the other terminal to the respective node Dn for connection between the load Ln and the circuit 1.

A typical number of inductive loads for automotive applications is N=8, for example. For simplicity, the description to follow will refer to a portion of the circuit 1 relating to a single inductive load, the first load L1, for example.

The active element T1 for driving the load L1 comprises an N-channel MOS transistor. Preferably, this would be a power transistor in applications where the inductive load driving current is fairly large. The transistor T1 has a drain terminal connected to the node D1 and a source terminal to ground.

The regulator means 21 for recycling control comprises a diode D11 having its cathode connected to the potential reference Vref and its anode connected to an input leg of a current mirror, also included in the block 21 and comprising a pair of bipolar transistors Q11 and Q21 both of which are of the pnp type in this embodiment. An output leg of the current mirror Q11-Q21 is connected to the control terminal DR1, specifically comprised of a gate terminal of the transistor T1.